DY 35: Statistical Physics of Biological Systems I (joint session BP/DY)

Time: Thursday 9:30–13:00 Location: TOE 317

DY 35.1 Thu 9:30 TOE 317

Reduced stochastic models of drifting assemblies in plastic neuronal networks — •Sven Goedeke, Christian Klos, Yaroslav Felipe Kalle Kossio, and Raoul-Martin Memmesheimer — University of Bonn, Bonn, Germany

In a standard model, associative memories are represented by assemblies of strongly interconnected neurons. It has recently been proposed that these assemblies are not static but drift freely in neural circuits. On the level of single neurons, assembly drift is reflected by characteristic dynamics: relatively long times of stable assembly membership interspersed with fast transitions. How can we mechanistically understand these dynamics? Here we answer this question by proposing simplified, reduced models. We first construct a random walk model for neuron transitions between assemblies based on the statistics of synaptic weight changes measured in simulations of spiking neural networks exhibiting assembly drift. It shows that neuron transitions between assemblies can be understood as noise-activated switching between metastable states. The random walk's potential landscape and inhomogeneous noise strength induce metastability and thus support assembly maintenance in the presence of ongoing fluctuations. In a second step, we derive an effective random walk model from first principles. In this model, a neuron spikes at a fixed background rate and with an input weight-dependent probability when its current or another assembly reactivates. The approach can be applied generally to networks of drifting assemblies, irrespective of the employed neuron and plasticity models.

DY 35.2 Thu 9:45 TOE 317

Fluctuation-dissipation relations for spiking neurons — •Benjamin Lindner — Bernstein Center for Computational Neuroscience Berlin, Philippstr. 13, Haus 2, 10115 Berlin, Germany — Physics Department of Humboldt University Berlin, Newtonstr. 15, 12489 Berlin, Germany

Spontaneous fluctuations and stimulus response are essential features of neural functioning but how they are connected is poorly understood. I derive fluctuation-dissipation relations (FDR) between the spontaneous spike and voltage correlations and the firing rate susceptibility for i) the leaky integrate-and-fire (IF) model with white noise; ii) an IF model with arbitrary voltage dependence, an adaptation current, and correlated noise. The FDRs can be used to derive thus far unknown statistics analytically [model (i)] or the otherwise inaccessible intrinsic noise statistics [model (ii)].

DY 35.3 Thu 10:00 TOE 317

Current fluctuations in nanopores: origin and breakdown of 1/f noise — •Paul Robin, Mathieu Lizee, Alessandro Siria, and Lydéric Bocquet — ENS, Université PSL, CNRS, Sorbonne Université, Université Paris-Cité, Paris, France

Ion transport through nanometric pores is key to many biological processes, from osmoregulation to neurotransmission, yet this process is known to occur under strong fluctuations. The power spectrum of this current noise is known to scale like 1/f at low frequency, according to the long-standing yet empirical Hooge law. Modelling attempts generally rely on complex assumptions such as self-organized criticality or microscopic disorder - in contrast with the apparent universality of 1/f pink noise. In this talk, I will present a simple theoretical model accounting for the presence of 1/f fluctuations in ionic currents through nanopores regardless of their microscopic structure. In particular, I will show how pink noise can emerge from diffusive processes alone, rather than necessitating complex conductance switching mechanisms. This prediction also explains why pink noise can be observed for frequencies much lower than that of microscopic processes. Lastly, I will discuss under which conditions this description is expected to break down. Notably, chemical processes on the pore's walls can alter ion dynamics and slow down diffusion, leading to memory effects and deviations to Hooge's law. I will compare these predictions to experimental data on artificial nanofluidic pores with various surface properties and reactivities.

DY 35.4 Thu 10:15 TOE 317

Selective alignment force in schooling fish linked to leader-follower interactions given by relative speeds of neighbours — •Andreu Puy[1], Palina Bartashevich[2,3], and Pawel Romanczuk[2,3] — [1]Departament de Física, Universitat Politècnica de Catalunya, Barcelona, Spain — [2]Institute for Theoretical Biology, Humboldt-Universität zu Berlin, Germany — [3]Excellence Cluster Science of Intelligence, Technische Universität Berlin, Germany

Collective motion is commonly assumed to emerge when individuals in a group interact with neighbours via some combination of attraction, repulsion and alignment forces. Alignment has been the most elusive and controversial force to study in experimental setups, with previous works differing about its existence. Here we revisit the topic by introducing a force map technique depending on the relative velocities of neighbours. In contrast to commonly used force maps, our technique demonstrates evidence for experimental data of schooling fish of a selective alignment force when individuals move at slower speeds than their neighbours and an antialignment force when they move at higher speeds. We employ a simple model with alignment to demonstrate the validity and robustness of the proposed force map. Including a selective interaction where individuals only interact with faster neighbours allowed us to reproduce the alignment interactions in the experimental data. Finally, we link this idea to leader-follower interactions, justifying that faster individuals act as leaders with respect to their neighbours.

Invited Talk DY 35.5 Thu 10:30 TOE 317

Statistical Physics of Spatially Organized Catalytic Particles — •Ulrich Gerland — Technical University of Munich, Germany

Catalytic particles are spatially organized in a number of biological systems across different length scales, from enzyme complexes to metabolically coupled cells. Despite operating on different scales, these systems all feature localized reactions involving partially hindered diffusive transport, which is determined by the collective arrangement of the catalysts. We explore how different arrangements affect the interplay between the reaction and transport dynamics, which ultimately determines the flux through the reaction pathway. Two fundamental trade-offs arise, the first between efficient inter-catalyst transport and the depletion of substrate, and the second between steric confinement of intermediate products and the accessibility of catalysts to substrate. We find that the question of optimal catalyst arrangements generalizes the well-known Thomson problem of electrostatics [1]. Furthermore, we map the problem of optimally arranging enzymes to an economic investment problem, which helps to formulate and understand a possible design principle for synthetic biomolecular systems [2].

[1] F. Hinzpeter, F. Tostevin, A. Buchner, and U. Gerland (2022), Trade-offs and design principles in the spatial organization of catalytic particles, Nature Phys. 18, 203-211.

[2] G. Giunta, F. Tostevin, S. Tanase-Nicola, and U. Gerland (2022), Optimal spatial allocation of enzymes as an investment problem, Commun. Phys. 5, 319.

15 min. break

DY 35.6 Thu 11:15 TOE 317

Collective Dynamics of Multi-Scale Interacting Complex Systems — •Fabrizio Olmeda[1,2] and Steffen Rulands[1,3] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden, Germany — [2]IST Austria, Vienna, Austria — [3]Ludwigs-Maximilians-Universitat Munchen, Arnold Sommerfeld Center for Theoretical Physics, Munich, Germany

Understanding the conditions under which complex systems are stable is pivotal for understanding their response to perturbations. Theoretical work has shown that for global interactions between components a minimal complex system is stable if the standard deviation of linearised interaction rates is sufficiently small. In biological systems, which often contain a small number of important and interactions are mediated by diffusing agents, stochasticity and non-locality may influence stability. Here, we generalise these results to stochastic, spatial systems with interaction on multiple length scales. Starting from a microscopic description we derive a coarse-grained field theory and identify a transition between a regime defined by giant density fluctuations and one exhibiting a spatial instability with a finite wave length. The latter is suppressed by non-reciprocity in the interactions between components. Our work provides a rigorous framework to infer col-

lective dynamics and stability in complex systems, with applications ranging from ecosystems to morphogenesis.

DY 35.7 Thu 11:30 TOE 317

Physical mechanism of erythrocytes sedimentation rate — •Alexis Darras, Thomas John, Lars Kaestner, and Christian Wagner — Experimental Physics, Saarland University; D-66123 Saarbrücken, Germany

Red blood cells (or erythrocytes) sedimentation rate (ESR) is a physical parameter of blood which is often checked in medical diagnosis. It is indeed well known that in case of inflammation, the increase in fibrinogen and other proteins induces a higher ESR.

Until recently, researchers thought that the increase of fibrinogen accelerates the ESR by creating bigger aggregates of red blood cells (RBC). Fibrinogen is indeed an aggregation agent of RBCs, and bigger aggregates tend to sediment faster in Stokes regime. However, modeling the ESR measurements with this hypothesis is challenging and often requires physical assumptions specific to this system.

Besides, modern colloidal science has shown that attractive particles, in suspensions with a high volume fraction, form percolating aggregates, as wide as the container. The sedimentation of those colloids then follows a so-called "colloidal gel collapse" regime, governed by the geometry of the percolating aggregate acting as a porous material. In this talk, we show that RBCs actually follow the same behavior. We also demonstrate that a porous-material model naturally leads to an efficient description the RBC sedimentation, which also provides a long-sought dependency of the ESR as a function of the initial RBC volume fraction (i.e. the hematocrit).

DY 35.8 Thu 11:45 TOE 317

Stochastic wavelength selection and pattern fixation — •Tom Burkart[1,2], Anastasiia Petrova[2,3], Laeschkir Würthner[1,2], Claudia Veigel[2,3], and Erwin Frey[1,2,4] — [1]Arnold Sommerfeld Center for Theoretical Physics (ASC), Department of Physics, LMU München, Munich, Germany — [2]Center for NanoScience, LMU München, Munich, Germany — [3]Department of Cellular Physiology, Biomedical Center (BMC), LMU München, Planegg-Martinsried, Germany — [4]Max Planck School Matter to Life, Munich, Germany

Biological pattern-forming processes are typically driven by a chemical fuel (out-of-equilibrium systems) or by a relaxation towards a thermodynamic equilibrium (phase separation). In these cases, pattern wavelength selection results from translational shifts of high-density regions and mass redistribution in between such regions. Here, we study how a pattern with a characteristic wavelength can form when high-density regions can only grow, but neither mass redistribution nor translation are allowed. The corresponding wavelength selection mechanism relies on thermal fluctuations, irreversible fixation of randomly occurring high-density regions, and long-ranged interactions between these regions. To model the density dynamics and the long-ranged interaction, we derive a set of reaction-diffusion equations from a free energy functional. In addition, we derive the statistics of pattern wavelengths from order statistics, emphasising the stochastic nature of the underlying mechanism. Our results constitute an alternative path to pattern formation next to out-of-equilibrium dynamics and phase separation processes.

DY 35.9 Thu 12:00 TOE 317

Control of non-equilibrium chemical reactions via phase separation — •Sudarshana Laha[1,2], Jonathan Bauermann[1,2], Tyler S. Harmon[3], Frank Jülicher[1,2], Thomas C.T. Michaels[4], and Christoph A. Weber[5] — [1]Max Planck Institute for the Physics of Complex Systems Dresden , Germany — [2]Center for Systems Biology Dresden , Germany — [3]IFW Dresden, Germany — [4]ETH Zürich, Switzerland — [5]Institute of Physics, University of Augsburg, Germany

Fuel-driven out-of-equilibrium chemical reactions are spatially organized using compartments in living cells. To what extent the properties of chemical reactions are altered by the compartments relative to homogeneous systems and the underlying physical principles are less explored. Here, we derive a theoretical framework to study such chemical reactions in the presence of compartments. We highlight the different governing kinetic equations for the reactants in diffusion-limited and reaction-limited regimes. We show that for two-state transition processes, the turnover of the product can be significantly affected in the limit of infinitely fast diffusion of the components. We can further derive the optimal compartment volume analytically which shows how phase separation parameters can affect the turnover. We further observe that the initial rate can be strongly modified for enzymatic and nucleation processes. These aspects allow us to understand better the control of such processes and exemplify the role of enzymes in compartments to speed up the reaction. This understanding is crucial for synthetically designing of cells as compartments and establishing communication between them.

DY 35.10 Thu 12:15 TOE 317

Microphase separation of living cells — •François Detcheverry, Adrien Carrère, Joseph d'Alessandro, Olivier Cochet-Escartin, Julie Hesnard, Nasser Ghazi, Charlotte Rivière, Christophe Anjard, and Jean-Paul Rieu — University of Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622, VILLEURBANNE, France

Self-organization of cells is key to a variety of biological systems and physical concepts inspired from condensed matter have proven essential in understanding some of their properties. Here we demonstrate that microphase separation, long known in polymeric materials and other inert systems, has a natural counterpart in living cells. When placed below a millimetric film of liquid nutritive medium, a quasi two-dimensional population of *Dictyostelium discoideum* cells spontaneously self-assembles into compact domains. Their typical size of 100 μm is governed by a balance between competing interactions: an adhesion which acts as a short-range attraction and promotes aggregation, and an effective long-range repulsion stemming from aerotaxis in near anoxic condition. We present a combination of experimental data, analytical modelling and cell-based simulations that all support this scenario. Our findings establish a generic mechanism for self-organization of living cells and highlight oxygen regulation as an emergent organizing principle for biological matter.

[Preprint: bioRxiv https://doi.org/10.1101/2022.05.25.493184]

DY 35.11 Thu 12:30 TOE 317

Hydrationa and crowding effects on SOD1 sequestration into FUS biocondensates — Luis Enrique Coronas[1], Emeline Laborie[2], Stepan Timr[2], Fabio Sterpone[2], and •Giancarlo Franzese[1,3] — [1]Interdisciplinary and Statistical Physics Section–Department of Condensed Matter Physics, Physics & Institute of Nanoscience and Nanotechnology (IN2UB), Universitat de Barcelona, Barcelona, Spain — [2]CNRS Laboratoire de Biochimie Théorique, Institut de Biologie Physico-Chimique, Université Paris Denis Diderot, Paris, France — [3]Max Planck Institut für Physik Komplexer Systeme, Dresden, Germany

Superoxide Dismutase 1 (SOD1) is a protein related to amyotrophic lateral sclerosis that, under Heat Stress (HS), is sequestered into Stress Granules in vivo and Fused in Sarcoma (FUS) biomolecular condensates in vitro. Experiments show that an in vitro cytomimetic medium, using Bovine Serum Albumin (BSA) as crowder, decreases the SOD1 partition coefficient (PC) even after 60 min of HS. Implicit-water OPEP simulations show no preferential interactions of SOD1 with BSA. Here, by combining the OPEP with a coarse-grained water model, accounting for water contributions to the interactions in large biological systems, we show that SOD1 has one preferred associative state in FUS but three in BSA, whose transition rates and residency times are controlled by their hydration. We conclude that the SOD1 PC's decrease in FUS condensate, when BSA crowders are present, is due to the hydration entropy increase in BSA, a mechanism possibly relevant also in vivo.

DY 35.12 Thu 12:45 TOE 317

Stochastic heat production in phase-separated systems out of equilibrium — •Kathrin Laxhuber, Jonathan Bauermann, and Frank Jülicher — Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

Phase-separated multi-component systems in the presence of chemical reactions provide interesting examples of non-equilibrium systems. We complement the dynamics of phase separation by a heat transport equation which is coupled to diffusive matter transport. On a microscopic scale, fluctuations become relevant, which we include by developing a stochastic lattice model that we link to the macroscopic continuum dynamics. We then implement this model in a kinetic Monte Carlo simulation of spatial flows of energy and matter as well as local reactions. By coupling to reservoirs or by fueling reactions, a system can be driven out of equilibrium. Using a toy system of a single phase-separated droplet, we discuss how temperature fluctuations affect the droplets' dynamics and the noise in the system. We furthermore show how the fluxes due to the driving give rise to a stochastic production of

latent heat and reaction heat. The systems we discuss serve as models for biological condensates and the study of energetics in cells.